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Micromachined Sensor and Actuator Research at Sandia's Microelectronics Development Laboratory

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Abstract

An overview of the surface micromachining program at the Microelectronics Development Laboratory of Sandia National Laboratories is presented. Development efforts are underway for a variety of surface micromachined sensors and actuators for both defense and commercial applications. A technology that embeds micromechanical devices below the surface of the wafer prior to microelectronics fabrication has been developed for integrating microelectronics with surface-micromachined micromechanical devices. The application of chemical-mechanical polishing to increase the manufacturability of micromechanical devices is also presented.

Facility

The Microelectronics Development Laboratory (MDL), shown in Figure 1, at Sandia National Laboratories is a 30,000 square foot, class 1 semiconductor fabrication facility located in Albuquerque, NM. The MDL is a modern, well-equipped CMOS fabrication facility with both 2 μm and 0.5 μm CMOS technologies. The facility has been adapted to enable the advancement of other technologies, such as micromechanics, in addition to the continued development of sub-micron CMOS. Micromechanics benefits from the wide variety of equipment and processes in existence to support the baseline CMOS, but are constrained by CMOS compatibility issues.

In the area of micromechanics, the MDL has development projects in both surface and bulk micromachining, although surface micromachining constitutes the majority of the MDL's efforts and is emphasized here.

Figure 1. The Microelectronics Development Laboratory at Sandia National Laboratories in Albuquerque, NM.

Process and Materials Development

Chemical-Mechanical Polishing

Recently, chemical-mechanical polishing (CMP) has emerged as an enabling technology for the manufacturing of multi-level metal interconnects used in high-density integrated circuits.[1] At Sandia, we are extending the use of CMP from sub-micron IC manufacturing to the fabrication of more advanced and complex surface-micromachined micro-electromechanical systems (MEMS).[2] CMP is becoming a critical enabling technology in the development and manufacturing of complex MEMS.

As relatively thick (~2 μm) layers of polysilicon and oxide are deposited and etched, considerable surface topography arises which imposes limitations in deposition, patterning, and etching of subsequent layers. Specifically, it is desirable to planarize each layer in order to eliminate processing difficulties associated with photoresist step coverage, depth-of-focus of photolithography equipment, and stringer generation during dry etch. Presently, other researchers address these problems through careful design of structures, special photoresist processes, and the use of extra mask levels.

The SEM cross-sections illustrated in Figures 2 and 3 depict the surface topography before (Figure 2) and after (Figure 3) CMP of a CVD TEOS film deposited on patterned polysilicon devices. This demonstrates the effectiveness of CMP for planarizing sacrificial oxide layers deposited over MEM structures.

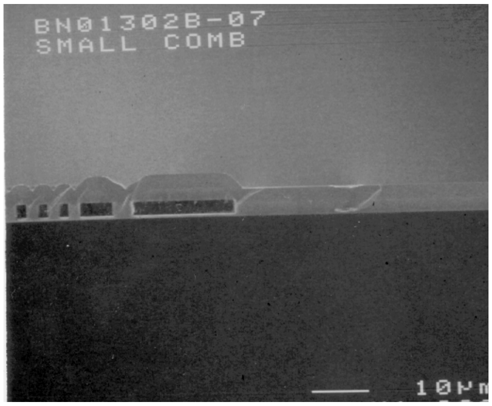

Figure 2. Cross-section of a partially fabricated micromachine showing the uneven topography before CMP planarization.

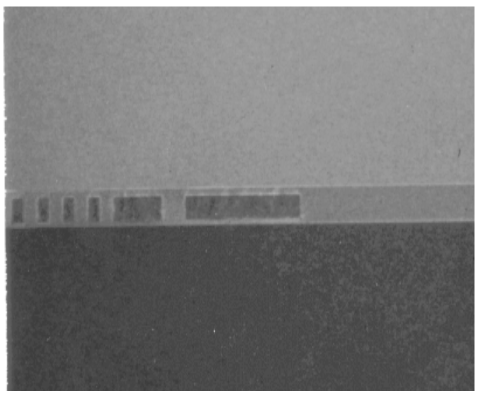

Figure 3. Cross-section of a partially-fabricated micromachine after CMP planarization.

CMP is also being used in the fabrication of other micromechanical devices including the planar pressure sensor and integrated MEMS/CMOS technologies mentioned previously along with a high-aspect-ratio, molded tungsten proof mass[3] for an accelerometer.

Multi-Level, Ultra-Flat Polysilicon

Multiple levels of structural polysilicon are needed to design complex micromachines such as the microengine and microtransmission discussed later in this paper. Although many sensors only need a ground plane and two structural levels of polysilicon, actuators benefit immensely from the ability to created linkage arms between rotating gears that are, themselves, also free to rotate. Additionally, large complex structures require extremely small levels of residual stress and stress gradient within completed polysilicon devices. Figure 4, a set of typical test structures[4] built using Sandia's technology, illustrates these extremely small residual stress and stress gradient levels.

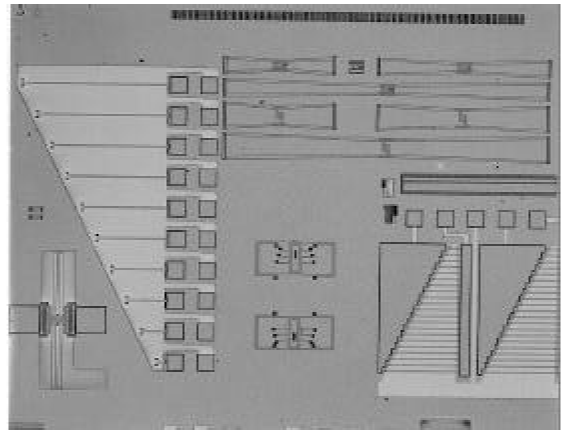

Figure 4. Polysilicon mechanical properties test structures built with Sandia's ultra-flat polysilicon process. Cantilever beams as long as 950 μm and bowtie structures as long as 2000 μm have been fabricated with significantly less than 1 μm of deflection. These small deflections indicate extremely low stress gradients and stresses, respectively, for the structural polysilicon.

High-Aspect-Ratio Micromachining

In addition to its uses for planarization of surface-micromachined devices, CMP plays a key role in the fabrication of high-aspect ratio micromolded polysilicon and tungsten devices. In the technology presented here[3], deep, narrow trenches lined with oxide are filled with thin films (~2-5 µm) of either polysilicon or tungsten and then planarized with CMP. These structures can be integrated with surface micromachined polysilicon structures to form large high-aspect-ratio proof masses with compliant surface-micromachined springs as shown in Figure 5.

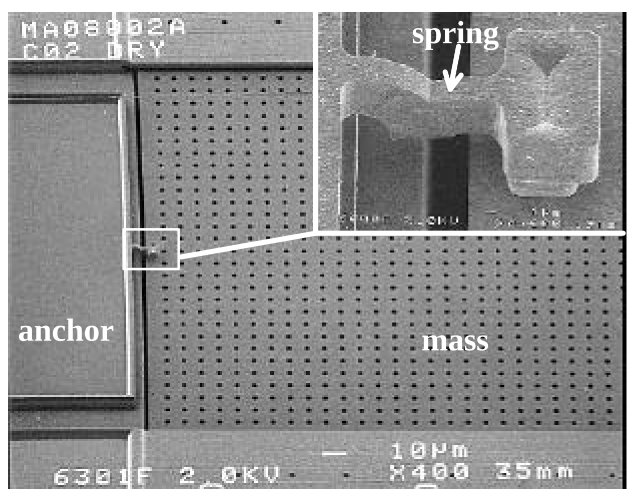

Figure 5. High-aspect-ratio polysilicon accelerometer mass integrated with a surface-micromachined spring

CMOS/Micromechanics Integration

Processes for integrating micromechanical devices with their controlling electronics have also been developed. As recently summarized in a review paper by Howe[5], micromechanical structures require long, high-temperature anneals to ensure that the stress in the structural materials of the micromechanical structures has completely relaxed. On the other hand, CMOS technology requires planarity of the substrate to achieve high-resolution in the photolithographic process. If the micromechanical processing is performed first, the substrate planarity is sacrificed. If the CMOS is built first, it (and its metallization) must withstand the high-temperature anneals of the micromechanical processing. This second alternative was chosen by researchers at U. C. Berkeley[6] and has been examined at the MDL. In this approach, the standard aluminum metal used in CMOS is replaced with tungsten. Since tungsten is a refractory metal, it withstands the high-temperature processing. However, a number of issues remain unsolved concerning the adhesion of the tungsten layer and the unwanted formation of tungsten silicides. Despite these issues, the MDL has fabricated integrated devices with functioning control electronics, although both device yield and performance were less than optimal.

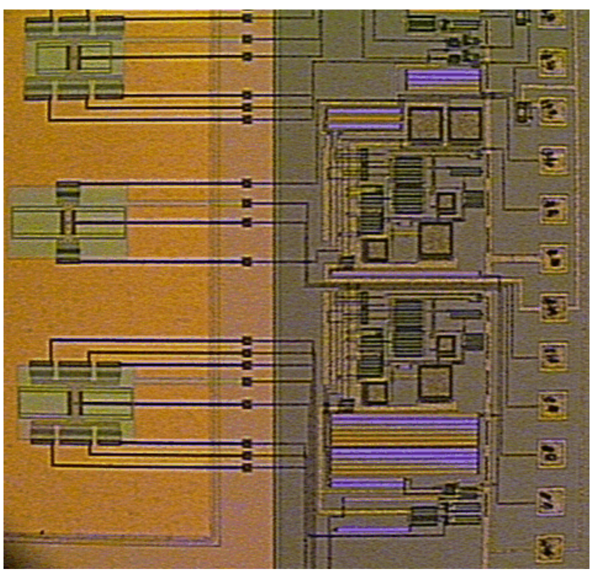

Figure 6. Micromachined resonators (left) next to their CMOS driving electronics (right) fabricated using the embedded micromechanics integration process.

A unique micromechanics-first approach[7] has also been developed at Sandia. In this approach, micromechanical devices are fabricated in a trench etched on the surface of the wafer. After these devices are complete, the trench is refilled with oxide, planarized using chemical-mechanical polishing, and sealed with a nitride membrane. The wafer with the embedded micromechanical devices is then processed using conventional CMOS processing. Additional steps are added at the end of the CMOS process in order to expose and release the embedded micromechanical devices. Completed devices are shown in Figure 6. A cross-section of this technology is shown in Figure 7. The yield of the most recent lots fabricated using this process has exceeded 98% for integrated combustible gas detection systems.

A collaboration with designers from the Berkeley Sensor and Actuator Center (BSAC) has recently started. BSAC designs for inertial measurement units (three-axis acceleration[8] and three-axis rotation rate[9,10]) have been ported to Sandia's Modular, Monolithic Micro-Electro-Mechanical Systems (M^3EMS) technology. Initial lots of devices have been fabricated and the results from these designs will be reported by BSAC.

This technology has also been named as one of the recipients of the 1996 R&D 100 Award.

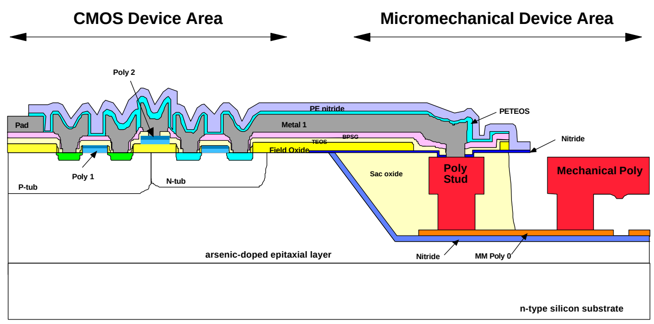

Figure 7. A schematic cross-section of the embedded micromechanics approach to CMOS/MEMS integration.

Sensors

Pressure Sensors

A planar pressure sensor technology similar to a non-planar technology developed at U. of Wisconsin[11] has been developed at the MDL[12] based upon a silicon nitride layer as the diaphragm material. A trench is etched ~2 microns deep in the surface of a silicon wafer. This trench is refilled with a sacrificial oxide and planarized with chemical-mechanical polishing. A silicon nitride diaphragm layer is then deposited. The sacrificial oxide underneath this diaphragm layer is etched using HF leaving a cavity beneath the diaphragm. An additional silicon nitride layer is used to seal the cavity in near-vacuum conditions (approx. 200 mTorr). Polysilicon piezoresistors are deposited on the diaphragm to sense the diaphragm strain that results from changes in ambient pressure. A completed, 100-micron-diameter planar pressure sensor is shown in Figure 8. The sensor's response is illustrated in Figure 9.

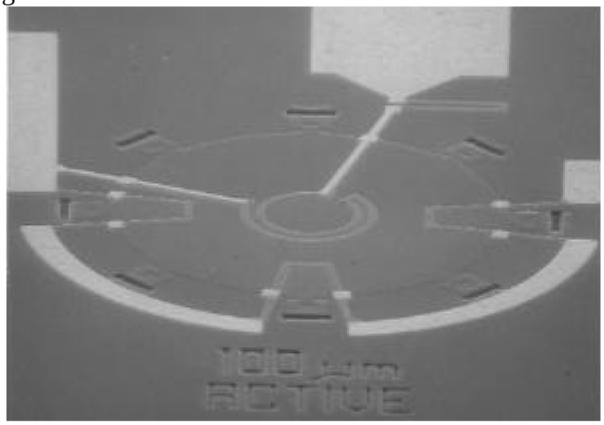

Figure 8. An SEM of a planar, surface-micromachined pressure sensor. The pressure sensor uses polysilicon piezoresistors on a nitride diaphragm over a vacuum cavity to sense changes in ambient air pressure.

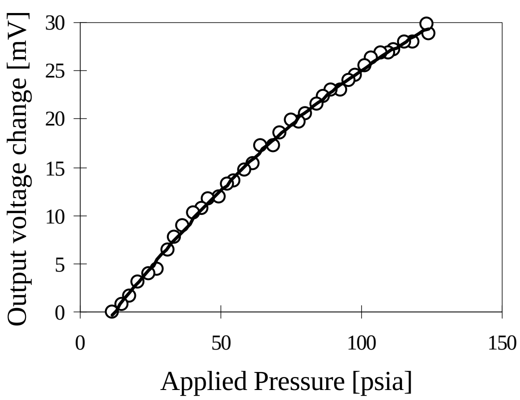

Figure 9. Output voltage vs. applied pressure for a 100 µm diameter pressure sensor.

Combustible Gas Sensors

Surface micromachined polysilicon filaments similar to those developed by researchers at U.C. Berkeley[13] for use as catalytic gas sensors, flow sensors, and thermal-conductivity pressure gauges have been fabricated using a single-level doped polysilicon process. A sacrificial oxide is patterned to form both the anchor layer and a stiction-reducing dimple level. A scanning electron micrograph (SEM) of a differential pair of filaments is shown in Figure 10. One of these filaments is passivated with silicon nitride while the other is selectively coated with a platinum catalyst.[14] These filaments have been used to detect combustible gas mixtures and can clearly detect levels as low as 100 ppm of H_2 in air as shown by the sensor response in Figure 11. The filament pairs consume milliwatts of power when operated in a continuous mode and can be operated in pulsed mode to reduce the average power consumption to microwatts.

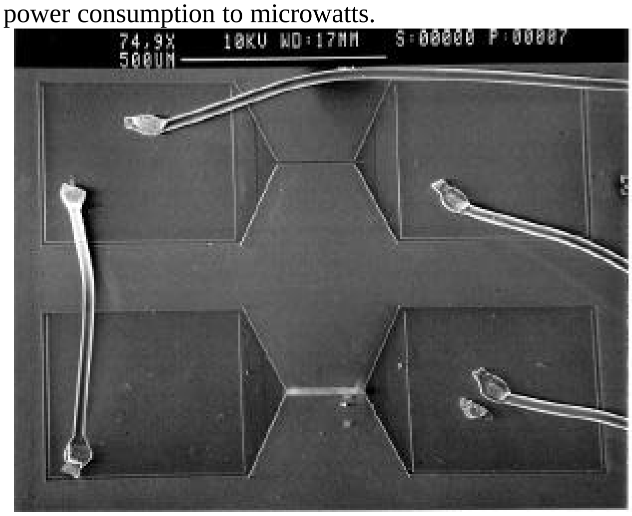

Figure 10. Two polysilicon filaments for use as a combustible gas detector. The upper filament is passivated with silicon nitride. The lower filament has been selectively coated with a platinum catalyst.

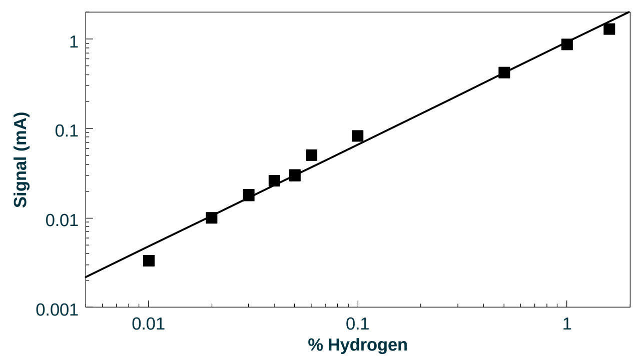

Figure 11. The signal change from the detector pair shown in Figure 10 to various concentrations of hydrogen in a 20% oxygen ambient.

Actuators

µEngine

Micromechanical actuators have not seen the wide-spread industrial use that micromechanical sensors have achieved. Two principal stumbling blocks to their widespread application have been low torque and difficulty in coupling tools to engines. The MDL has developed devices that overcome these issues. Our three-level polysilicon micromachining process[15,16] enables the fabrication of devices with increased degrees of complexity that greatly enhance the ability to couple tools to engines.

This three-level process includes three movable levels of polysilicon in addition to a stationary level for a total of four levels of polysilicon. These levels are each separated by sacrificial oxide layers. A total of eight mask levels are used in this process. An additional friction-reducing layer of silicon nitride is placed between the layers that form bearing surfaces. The inset (lower right) to Figure 12 illustrates a bearing formed between two layers of mechanical poly. The overall photo in Figure 12 shows two comb-drive actuators[17] driving a set of linkages to a set of rotary gears. This engine can be rotated by applying sinusoidal driving forces 90^o out of phase with each other to each of the comb-drive actuators. Operation of the small gears (shown in the inset) at rotational speeds in excess of 300,000 revolutions per minute has been demonstrated. The operational lifetime of these small devices exceed $8x10^8$ revolutions. This smaller gear is shown driving a larger (1.6 mm diameter) gear[18] in Figure 12. This larger gear has been driven as fast as 4800 rpm.

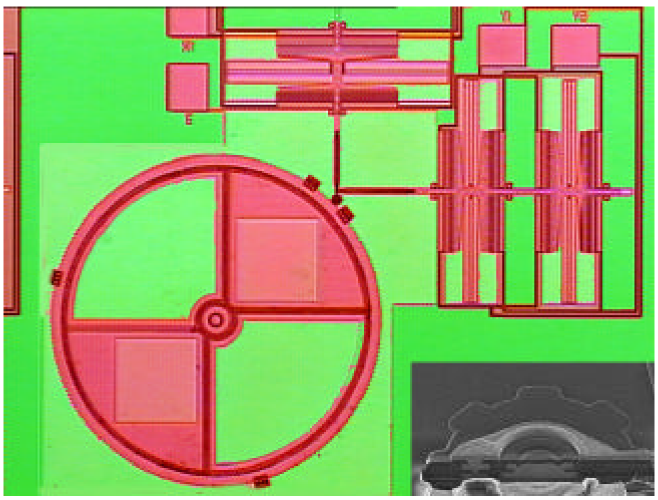

Figure 12. Two sets of linear comb-drive actuators driving the gear shown in the inset. This smaller gear drives a 1.6 mm diameter shutter in the lower left of the photo. Inset (lower right) shows a focused ion-beam cross-sectional image of the small gear.

µTransmission

To increase the torque available from a rotary drive, a multi-level microtransmission has been developed.[19] This transmission, shown in Figure 13, employs sets of small and large gears mounted on the same shaft that interlock with other sets of gears to transfer power while providing torque multiplication and speed reduction. The structure shown in Figure 13 couples the output gear of a microengine similar to the engine shown in Figure 12 to a rack and pinion unit that provides linear motion with high torque.

This transmission, the microengine described previously, a pin-in-maze discriminator, and a set of out-of-plane mirrors will be combined in future work to form a complete microlock.

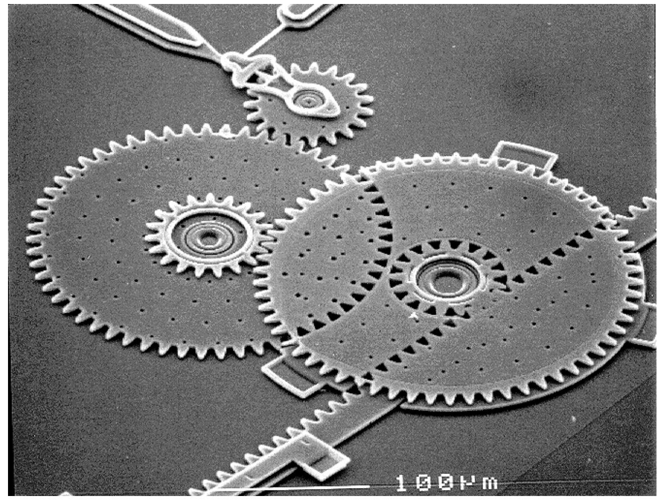

Figure 13. An electrostatic microengine output gear coupled to a double-level gear train that drives a rack and pinion slider. This gear train provides a speed-reduction/torque-multiplication ratio of 9.6 to 1.

Summary

Sandia's Microelectronics Development Laboratory has developed and is advancing a broad range of sensors and actuators based on polysilicon surface micromachining. CMP is being used to improve the manufacturability and reliability of MEMS technologies; it has become a critical enabling technology for the advancement of MEMS. Combustible gas detectors based on hot polysilicon filaments and pressure sensors based on sealed nitride diaphragms have been produced. A new technology where micromachined devices are embedded below the surface of a wafer prior to fabrication of microelectronic devices has also been developed. A three-level polysilicon process enables intricate coupling mechanisms that link linear comb-drive actuators to multiple rotating gears. This technology has been applied to microengines, microtransmissions, and microlocks.

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